Heat and Momentum Fluxes Near a Forest Edge

Kruijt, B.; Klaassen, W.; Hutjes, R.W.A.; Veen, A.W.L.

Published in:
Proceedings of the Symposium on Hydrological Interactions Between Atmosphere, Soil and Vegetation

Publication date:
1991

Hydrological Interactions Between Atmosphere, Soil and Vegetation (Proceedings of the Vienna Symposium, August 1991). IAHS Publ. no. 204, 1991.

Heat and Momentum Fluxes Near a Forest Edge

B. KRUIJT, W. KLAASSEN, R.W.A. HUTJES & A.W.L. VEEN
Department of Physical Geography, University of Groningen, Kerklaan 30, 9751 NN Haren (Gr.), Netherlands

ABSTRACT Turbulent fluxes have been measured downwind of an interface between agricultural land and mixed deciduous forest. Theory predicts the presence of vertical flux divergences within the adjusting layer of air. It was investigated whether edge effects and advection can be characterized by measured vertical flux change over the forest. Significant divergences were found, and it could be shown that flux profiles varied according to upwind surface conditions. Results suggest that many models predict a too fast adjustment of the air to a new surface after an edge.

INTRODUCTION

In the last two decades, much work has been done to understand the exchange of water and energy between forest and the atmosphere. This has resulted in considerable consensus among hydrologists and atmospheric scientists about the relevant processes in extensive homogeneous forests. However, in inhomogeneous forested terrain, there is still a lack of understanding in both the aereally integration of processes and the local effects of edges between surface types. Also, it is largely unknown how fluxes should be measured adequately in inhomogeneous situations. Measurements of fluxes near forest edges are scarce. Gash (1986) investigated the horizontal change of turbulence downwind of an edge just above a forest. The present paper aims to investigate whether effects of a forest edge can be characterized by measuring change of fluxes with height over a forest at some distance from an edge.

Over homogeneous terrain, the air flow is in equilibrium with the surface underneath. Since the only sources and sinks of heat and momentum are located at the surface, fluxes are constant with height above the surface. But after passing an edge, the flow will have to adjust to the new surface properties. Within the Internal Boundary Layer which develops downwind of a transition from low vegetation to forest, both horizontal and vertical divergences in fluxes are present. Horizontal divergences develop as a result of slow adjustment of the flow over and through the canopy. New surface fluxes can be expected to propagate upward as they are transported downstream. This results in vertical flux divergences, ideally representing the full transition from the changing surface fluxes to the upstream fluxes. A second reason for the existence of vertical divergences is associated with the different speed of adjustment to the forest of various air properties. The profiles of momentum, temperature and humidity adjust more slowly than their corresponding fluxes. Fluxes scale with u_* (proportional to the square root of momentum flux) and with the relevant gradients. So, a poorly adjusted gradient, together with well adjusted u_* may result in additional vertical flux divergences.

The processes involved in flow adjustment after a change in surface properties have been modelled by several authors (reviews by Brutsaert, 1982 and Claussen, 1988, Garratt, 1990). The models are different with respect to inclusion of pressure effects, treatment of within-canopy flow and parameterization of turbulent mixing. Fig.1, adapted from Claussen (1987) shows representative results of modelling vertical momentum flux divergences after a smooth-rough transition similar to the one this paper deals with. The model included pressure effects, but neglected within-canopy flow. As we see, several hundreds of metres after the edge, strong flux divergences are expected at heights of 30 to 100 m.

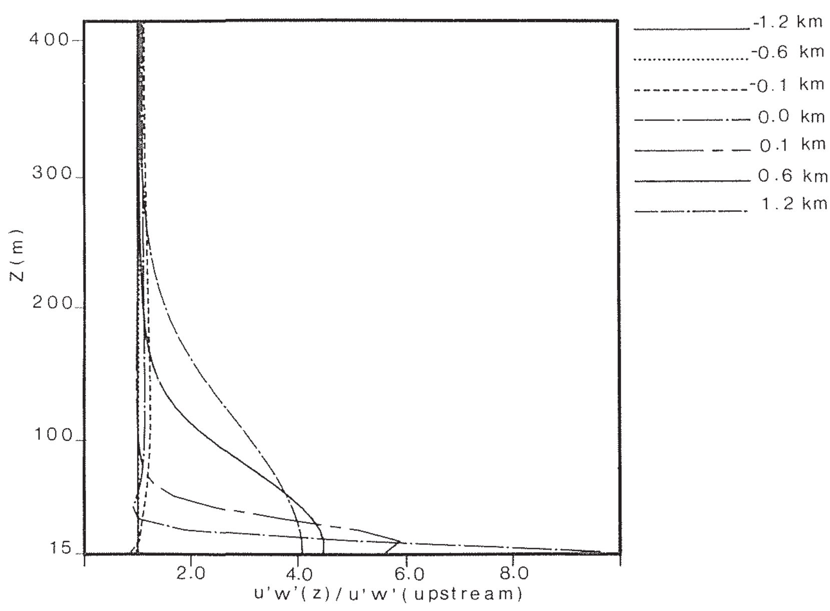

FIG. 1 Profiles of momentum flux with height z at several distances from a transition from roughness length z_0=0.02 m to z_0=2 m and a zero-plane displacement of 15 m. Adapted from Claussen, 1987, Fig 13b.

In measuring flux change with height over a forest, we must be aware of other possible causes for flux differences between measurement heights. First, small-scale inhomogeneities such as individual tree crowns and small gaps will lead to the same type of divergences as outlined above. But if these inhomogeneities are distributed randomly, the divergences will merely appear as scatter, since the wind never blows exactly from the same direction. Second, the so-called "Roughness Effect" (e.g. Garratt, 1978), may cause some doubt whether the constant flux assumption is at all valid close to the surface, even over homogeneous terrain. The "Roughness Effect" is associated with discrepancies between flux-profile theory and observations close to very rough surfaces, e.g. forest. Mostly, the ratio of gradients to fluxes is smaller than expected. Normally, over homogeneous terrain, only momentum fluxes can possibly increase in magnitude (i.e., get more negative!) with height just above the surface, because pressure gradients around roughness elements can act as a momentum sink. Therefore, the roughness effect is probably only caused by gradients of temperature, momentum and humidity that are smaller than expected, and not by fluxes that are larger close to the surface than at greater heights.

Very few published data exist of fluxes measured simultanuously at various heights. Over Thetford forest, UK, which has always been supposed to be homogeneous, de Bruin and Moore (1985) found a 2% per metre decrease with height in momentum flux magnitude, but they disregarded it. Högström et al. (1989) found heat and momentum flux divergences over forest at Jädraås, Sweden. From the above, it may be concluded that these divergences cannot be attributed to a roughness effect. Probably, they reflect some unnoticed horizontal inhomogeneity.

SITE AND INSTRUMENTATION

The work reported here was part of SHEAR, the Sleen Hydrometeorological Experiment on Advection and Regionalisation, described in detail by Kruijt & Van Den Burg, 1988. Fig. 2 shows the experimental area. Turbulent fluxes were measured at 3 or 4 levels, up to 12 m above a 21 m high, mixed deciduous forest stand (at tower 1, stand A in Fig.2) as well as at 9 m over adjacent extensive mixed agricultural land (Tower 2, area E in Fig. 2, further referred to as "Grassland"). The edge with the grassland was at 200 m to the west. To other directions, the stand was surrounded by 5-10 m high coniferous stands (B: low and sparse; C: well developed;Fig. 2) at 50 to 100 m n north to south-east, and by a 10 m high deciduous stand (D) 100 m south to south-west. Beyond these stands, the forest was extensive, mainly 10-20 m high and of varying composition (G in Fig 2). At 250 m NW, a small, forested patch of dried out bog was situated (F in fig. 2).

For the present paper, we made use of two data sets, collected in two 5-day periods in 1990, one in May and another in July. Over the forest, fluxes were measured at 25, 27 and 33 m. In May, an additional measurement height at 21 m had been installed. The 25, 27 and 33 m levels were equipped with fast-response 3-d Gill propeller anemometers and a fast-response thermocouple (Van Asselt et al., 1989). At 25 m and at 33 m, also a fast response hygrometer was mounted (Campbell Krypton Hygrometer). At 21 m a 3-d Sonic anemometer (Appied Technologies Inc.) and a thermocouple were used. The Gill anemometers were tilted, to minimize stalling errors. The instruments were frequently turned to face the mean wind direction, and were

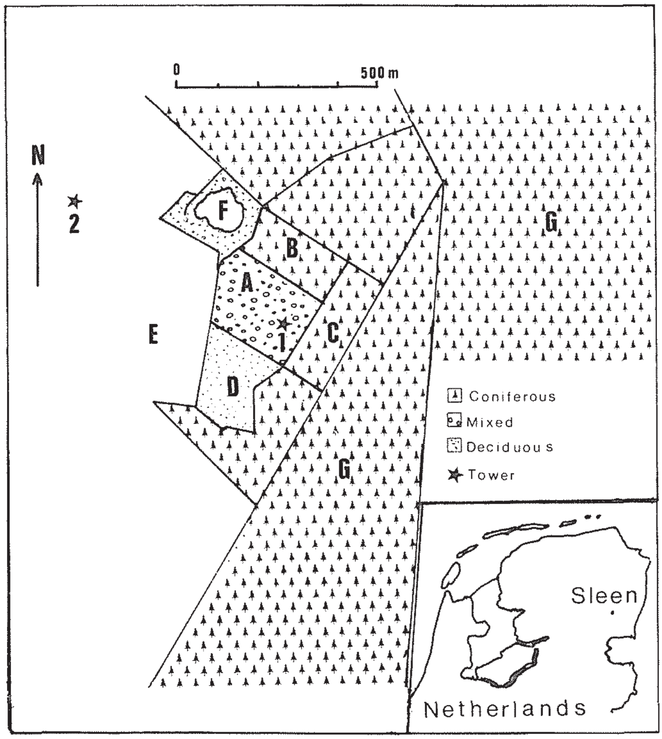

FIG. 2 Map of the SHEAR forest area with position of the towers and various surface types. Symbols are explained in the text.

mounted to 2.5 m booms on a very porous 0.8 m triangular tower. Over the grassland, we used a 1-d Campbell Sonic anemometer to measure vertical windspeed only, a fast-response cup anemometer (Vector instruments) and a very thin Campbell thermocouple. Thirty minute flux averages and other necessary statistics were obtained on-line from the relevant products of fluctuations around moving averages with a time constant of 1200 s (forest) or 800 s (grassland). The sampling rate was 10 Hz, and signals were continuously filtered for bad values. Off-line, fluxes were rotated to obtain values perpendicular to the mean flow direction, and a first-order correction for drift in the moving averages was applied (Shuttleworth, 1988). This setup provided sensible heat and momentum fluxes at all levels and sites, but latent heat fluxes were only collected at the 25 m and the 33 m level over the forest.

To be able to measure flux differences between heights accurately, we had to be sure that all instrument sets would yield equal fluxes if positioned at the same height. Therefore, an intercomparison test has been performed to compare several combinations of instruments. For this purpose, several combinations of two sets were mounted simultanuously at the top of the forest tower, and fluxes were collected as usual. The intercomparison showed no significant differences in latent heat fluxes, a 3% deviation in sensible heat fluxes, and a 9% deviation in momentum fluxes. It must be kept in mind that mounting instruments close to each other, as was done here, possibly introduced additional error by flow distortion effects. This error is likely to be less if instruments are mounted separately at different heights as was done in flux difference measurements.

RESULTS

From now on, we will refer to sensible heat fluxas H, to latent heat flux as LE, and u'w' will be the symbol for momentum flux divided by

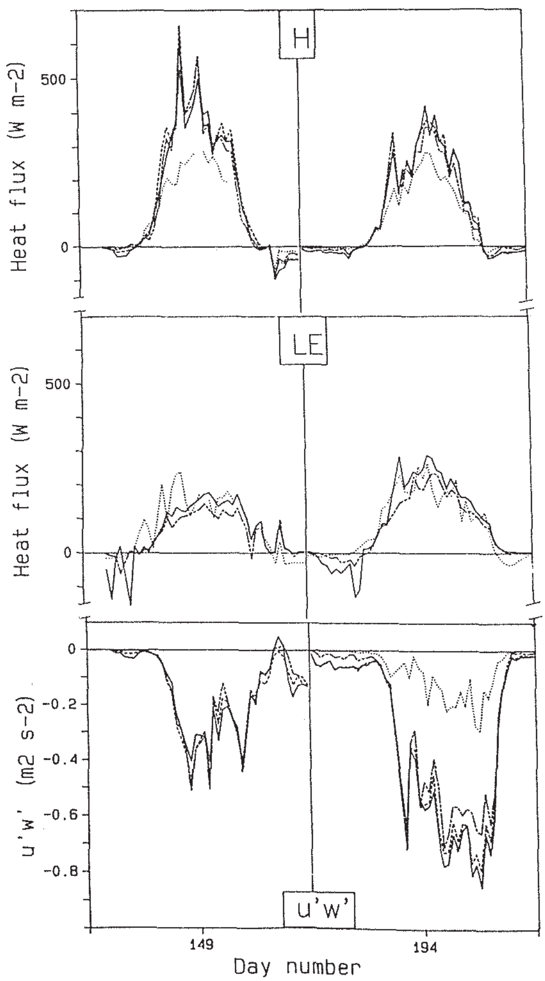

FIG. 3 Fluxes during two typical days, at: the grassland (·········), the forest at 25 m (———), 27 m (- - - - -), and 33 m (—— - - ——). For day 149, u'w' was not available over the grassland, and also over the grassland, for both days LE was estimated from the energy balance.

air density (i.e. $u'w'=u_*^2$). Fig. 3 shows the time series of these fluxes over the day for a typical day in each measurement period. The May period was dry and warm, with low winds from all directions. Leaves were not fully grown yet, and evaporation was low. The July period was sunny with moderate winds, mostly between west and south, but it was preceded by heavy rain. LE was higher in July than in May. As we see, all fluxes except LE were larger in magnitude over the forest than over the grassland. Flux totals were in good balance with available energy, which was higher in the forest than at the grassland.

For further analysis, all data were filtered to select only data points with heat fluxes all in excess of 5 W m^{-2}, u'w' smaller than -0.1 m^2 s^{-2} and mean wind speed in excess of 1 m s^{-1}. Only daytime values, during neutral to unstable stratification passed the filter. From the remaining data, relative flux divergences were calculated for each height interval (z1..z2) as follows:

$$D_F\ (z1..z2) = (F_{z2} - F_{z1}) / (F_{25}(z2-z1)) \qquad (1)$$

D_F(z1..z2) is the divergence of flux F per metre of height between z1 and z2, scaled with the flux at 25 m. F is H, LE or u'w', and (z1..z2) is one of the intervals (25..27), (25..33) or (27..33) (numbers are heights in metres). All divergences that were found in this way are plotted in Fig. 4 against mean wind direction at that moment. Scatter is considerable. Directions between south and west seem to be associated with the strongest divergences, but with other directions significant divergences seem to be present as well.

For further analysis of wind direction dependence, means and standard errors of the divergences calculated according to equation (1) were calculated for four wind direction classes: north (NW to NE), east (NE to SE), south (SE to SW) and west (SW to NW). From these, mean flux profiles were constructed for each class, by reconstructing divergences to differences relative to the 25 m flux. These are shown in Fig. 5. If the divergence between two levels was not significantly differing from zero, the marker at the higher level is not drawn. Between 21 m (average forest height) and 25 m, large divergences were found, especially for sensible heat fluxes. Except for northerly winds, flux profiles often showed an increase between 25 and 27 m, and then they decreased towards 33 m. Momentum flux decreased strongest between 27 and 33 m, with southerly and westerly winds. Sensible heat flux showed the same pattern, but with easterly winds divergences in H seemed to be even larger. With Norterly winds, divergences in u'w' and H were smallest. With latent heat fluxes, divergences were quite similar for all wind directions, but southerly winds showed the strongest effect on LE.
Relative differences of sensible heat and momentum fluxes between forest (25 m) and the grassland, i.e. $(F_{grass}-F_{25})/F_{25}$, have also been computed. For H, this was about -0.3, and for u'w', the relative difference was -0.8. Because LE was not measured over the grassland, we could not find such values for LE.

DISCUSSION

If the significant profiles of Fig. 5 are compared to the intercomparison test results, it can be concluded that nearly all

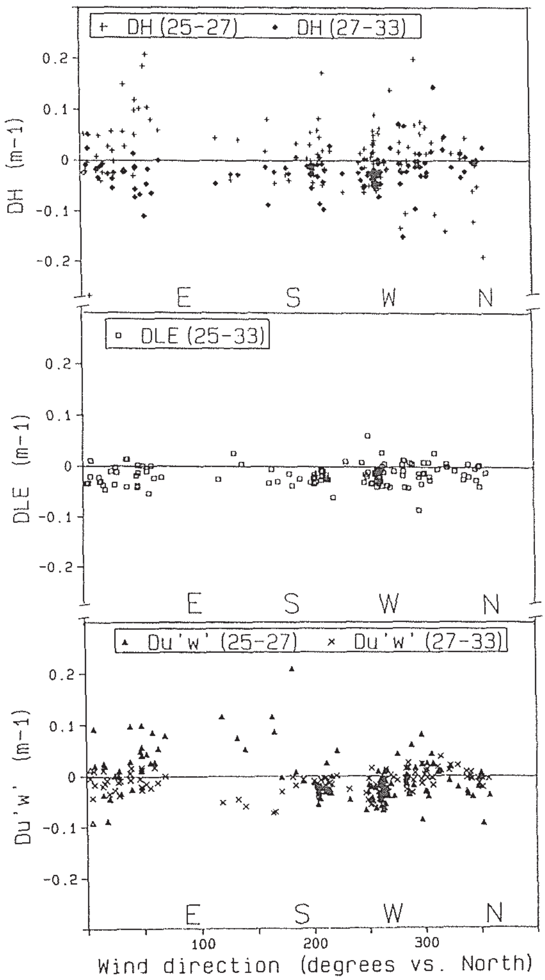

FIG. 4 Flux divergences over the forest, plotted against wind direction.

points were just outside an expected error range. For divergences of H and u'w', there was a clear dependence on wind direction. This justifies the conclusion that the observed divergences were not artifacts. Especially in the lowermost height intervals, local effects and minor sources and sinks of heat and momentum may have been responsible for the large divergences of varying sign that were observed. But the pattern between 25 and 33 m, often showing a flux increase, and then a decrease, has actually been computed in some model studies (e.g. Shir, 1972). These peaks in modelled flux profiles are associated with strong turbulence very near to the edge, and with different rates of adjustment of fluxes and profiles. However, those peaks were computed at larger scales than were observed in the present study. At present, it is difficult to speculate on the causes of latent heat flux divergences, since upwind measurements were lacking.

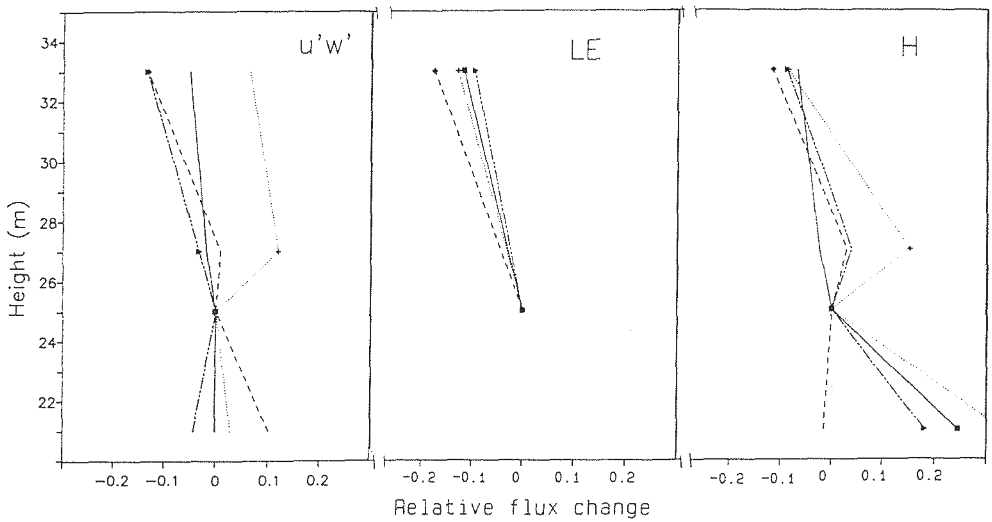

FIG.5 Mean relative flux profiles for four wind direction classes: N (——●——); E (······+······); S (– – ◆– – –); W (—·–▶–·). Non-significance of the divergences is indicated by omission of the marker above the height interval concerned.

If we compare Fig. 4 and Fig. 5, we find that the strong divergences found for the southern and western segment were mainly associated with SW winds. At this direction, the edge to the agricultural land was about 250 m away. Since the divergences from 27 to 33 were negative, the H and u'w' profiles at SW winds could have represented the lowermost part of a transition to the smaller grassland fluxes. The absence of significant divergences with northerly winds and the strong divergence in sensible heat flux associated with easterly winds might be explained as follows. The poorly developed stand B in fig. 2, which was to the north and differed to stand A in many aspects, was first expected to cause strong effects. But probably sensible heat fluxes and roughnesses were not very different to stand A. Apparently, the proximity (down to 50 m) of the eastern edge to stand C had a much stronger influence on divergences. If at this distance the temperature profile was not yet adjusted to the step-change in zero-plane displacement, strong divergences were very well possible.

CONCLUSIONS

Significant flux divergences were found which are related to edge effects and advection. The divergences that were found in the present study are in general larger than divergences modelled for a similar situation, like the example in Fig. 1. These models predict near constancy of fluxes within the height range in which we were measuring. Thus, the present data suggest that the available models for roughness transitions predict a too fast adjustment of the flow after a forest edge. Possibly models can be improved by better treatment of within-canopy flow, pressure effects, and slow adjustment of mixing length.

Further research will include improvement of models (Klaassen, in prep.) and more detailed investigations into the turbulence structure at the same locations over the forest and the grassland.

ACNOWLEDGEMENTS We are greatly indebted to H. de Groot and G.J. Van Den Burg, who kept the project running with technical support. Also, we thank Martin Claussen, GKSS Geesthacht, FRG, for fruitful discussions on edge effects. Han Dolman, presently at the Institute of Hydrology, UK, contributed to the design phase of the SHEAR project. The work was supported in part by the Working Group on Meteororlogy and Physical Oceanography (MFO) with financial aid from the Netherlands Organisation for Scientific Research.

REFERENCES

Brutsaert, W. (1982) Evaporation into the atmosphere. Reidel, Dordrecht, Netherlands.
Claussen, M (1987) The flow in a turbulent boundary layer upstream of a change in roughness. Boundary-Layer Meteorol. 40, 31-86.
Claussen, M (1988) Models of eddy viscosity for numerical simulation of horizontally inhomogeneous, neutral surface-layer flow. Boundary-Layer Meteorol. 42, 337-369.
De Bruin, H. A. R. and Moore C. J. (1985) Zero-plane displacement and roughness length for tall vegetation, derived from a simple mass conservation hypothesis. Boundary-Layer Meteorol. 31, 39-49.
Garratt, J. R. (1978) Transfer characteristics for a heterogeneous surface of large aerodynamic roughness. Quart. J. Roy. Met. Soc. 104, 491-502.
Garratt, J.R. (1990) The internal boundary layer - a review. Boundary-Layer Meteorol. 50, 171-203.
Gash, J. H. C. (1986) Observations of turbulence downwind of a forest-heath interface. Boundary-Layer Meteorol. 36, 227-237.
Högström, U., Bergström, H., Smedman, A., Halldin, S. & Lindroth, A. (1989) Turbulent exchange above a pine forest, I: Fluxes and gradients. Boundary-Layer Meteorol. 49, 197-217.
Klaassen, W. (in prep.) Average fluxes from heterogeneous vegetated regions.
Kruijt, B. & Van Den Burg, G. J. (1988) SHEAR: The Sleen Hydrometeorological Experiment on Advection and Regionalisation. Progress Report nr. 1. Rep. Dept. Phys. Geogr. and Soil Sci., Univ. of Groningen, Netherl. 27.
Shir, C. C. (1972) A numerical computation of air flow over a sudden change in surface roughness. J. Atmos. Sci. 29, 304-310.
Shuttleworth, W. J. (1988) Corrections for the effect of background concentration change and sensor drift in real-time eddy correlation systems. Boundary-Layer Meteorol. 42, 167-180.
Van Asselt, C. J., Jacobs, A. F. G., Van Boxel, J. H. & Jansen, A. E. (1989) A simple fast-response thermometer for outdoor use. Proc. TECEMO, W.M.O., Brussels, Sept. 1989.